Columbia University. Its solution is based on an argument outlined by Feynman in *The Character of Physical Law* (MIT Press, Cambridge, MA, 1967). We have to make what Albert calls a "past hypothesis" and assume that the universe started out in a low entropy state; it is important to realize that nothing less than that will do. It is a strange-but-true fact that if we try to understand in depth why the water in the bathtub cools down, we are quickly led to assumptions going back to the Big Bang.

The issue is a subtle one, because one might be tempted to deny the existence of the past altogether and to regard our memories of it as mere illusions. Of course, such an attitude would violently contradict common sense. It is, however, important to understand how one may reconcile our commonsense view (the past did exist) with our best physical theories (in particular, the mechanical account of the second law of thermodynamics). This reconciliation is very carefully discussed in the book. Essentially, assuming the existence of the past allows us to make sense of presently observed correlations (for example, that my house is where I remember having left it before traveling abroad).

A good part of the book is devoted to criticisms of frequent misconceptions in the physics literature, such as those on the role of ergodicity. The last chapter concerns quantum mechanics. There, the discussion is quite interesting and nicely summarizes the foundational issues associated with that theory, but Albert's final argument in favor of an intrinsically stochastic theory does not seem very convincing to me.

Albert has an idiosyncratic style, but a very pleasant one. Although this sounds like a cliché, he really is able to write both for intelligent teenagers and for specialists in philosophy of science. The foundations of statistical mechanics are often presented in physics textbooks in a rather obscure and confused way. By challenging common ways of thinking about this subject, *Time and Chance* can do quite a lot to improve the situation.

SCIENCE'S COMPASS

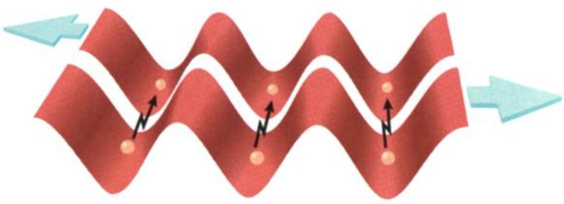
PERSPECTIVES: QUANTUM PHYSICS

No Mere Anarchy

Salman Habib

The study of quantum nonlinear systems is surprisingly young. Although Poincaré had understood key aspects of dynamical chaos (*1*) at the turn of the 20th century, and Einstein had realized its consequences for early quantum theory (*2*), quantum dynamics of nonlinear systems remained an obscure topic until the recent explosion of interest in quantum chaos. Sophisticated analysis (*3*, *4*) and greatly improved computational power have propelled many recent theoretical explorations of quantum chaos, and experimental progress has been no less rapid (*5*–*7*). In most cases, our intuition about quantum systems develops by thinking about them in classical terms, yet such intutions are hard to come by in systems that are chaotic. But it is just these systems that can produce surprising phenomena. A good example is chaos-assisted tunneling, the first experimental observation of which is presented by Steck *et al.* (*8*) on page 274 of this issue. Similar results have also been obtained recently by Hensinger *et al.* (*9*).

Quantum tunneling in the presence of an external barrier is theoretically well-understood in time-independent, one-dimensional systems. Classical physics may exclude particles from a spatial region, whereas quantum mechanically they are able to leak through. We can compute the magnitude of these effects by a variety of methods. However, as time dependence, or more dimensions, are added, the situation rapidly becomes more murky even in the case of integrable systems. Here, almost all classical trajectories live on n-dimensional surfaces in the $2n$-dimensional phase space. The isolation of classical trajectories on these invariant tori demonstrates that a potential barrier is no longer required to partition the classical phase space. According to the Kolmogorov-Arnold-Moser (KAM) theorem, small perturbations of integrable Hamiltonian systems will not destroy the tori but will leave most of them intact, albeit distorted and existing in a background of complex resonances and chaotic motion. As the size of the perturbation is increased, the generic case is that of a mixed phase space consisting of "regular islands" filled densely with tori and "stochastic seas," where no tori exist. A quantum initial state localized on one of the tori can evolve to another torus despite the fact that the corresponding classical trajectory cannot leave the original torus. This process is called dynamical tunneling (*10*). Direct dynamical tunneling occurs when the exact eigenstates are (approximate) linear combinations of the localized states, a situation analogous to a double-well system. Chaos-assisted tunneling (*11*), however, refers more specifically to the role of chaotic states near in energy to the localized states. Such states strongly influence the tunneling mechanism, leading to large and erratic variations in tunneling rates as an external parameter in the Hamiltonian is varied (in addition, there is no universal dependence on $\hbar$ for the tunneling amplitude).



Chaos-assisted tunneling. The potential felt by the atoms is a lattice of potential "wells," formed by a standing wave of laser light, in which the atoms can be confined. Because the intensity of the light is time-dependent, the wells become alternately shallower and deeper. Alternatively, the potential can be viewed as the sum of three lattices of constant amplitude: One of the lattices is stationary and does not participate in the tunneling, and the other two lattices move in opposite directions, as illustrated here (displaced for clarity). At the beginning of the experiment, atoms are trapped in the wells of the lattice moving to the right. The atoms then tunnel to the "mirror image" state, where they are trapped in the potential wells of the lattice moving to the left. The tunneling continues as the atoms oscillate between the two opposite motions.

Steck *et al.* studied the dynamics of cold cesium atoms in the presence of a time-dependent, cosine potential. There are essentially two regular islands, related by symmetry and surrounded by a large stochastic sea. With very precise velocity selection, the authors prepared an atomic ensemble in one of the islands and observed coherent oscillations between the islands by monitoring the momentum distribution of the atoms (see the figure).

To characterize the observed tunneling as chaos assisted, Steck *et al.* compare their results with the situation when chaos is absent. This they do by considering a time-averaged version of their potential, which is nothing but a quantum pendulum. In the case of the pendulum, the existence of a separatrix forbids classical transport across the $p =$

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0 (zero momentum) axis in phase space. The corresponding dynamical tunneling (high-order Bragg scattering) time scale is on the order of a second, whereas the tunneling time scale associated with the original potential is 400 μs. Repeating the experiment for the pendulum reveals no oscillations on the faster time scale, showing that this possible direct mechanism is absent in the main experiment.

The authors also present some remarkable data at high temporal resolution where they identify an oscillation between the initial peak and the chaotic region near $p = 0$. This oscillation proceeds at a rate faster than the tunneling period and directly suggests the importance of a third chaotic state in mediating the tunneling between the islands.

Future studies need to examine the dynamics of a single atom, as distinct from the ensemble experiments that have so far been the norm. By combining laser cooling techniques with cavity quantum electrodynamics, researchers have monitored the motion of single atoms over time scales of dynamical importance (*12*). The theory of continuous quantum measurement applied to this experimental situation predicts (noisy) trajectories for the atom, and these predictions have turned out to be in good agreement with the measurement record (*12*). As these experiments improve, one can look forward to a fuller explication of yet another key problem, the actual appearance of classical chaos from the underlying quantum dynamics (*13*).

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PERSPECTIVES: SUPERCONDUCTIVITY

Super Boron

T. H. Geballe

Discovering new superconductors has been an important way of gaining insight into superconductivity ever since that spectacular macroscopic quantum state was discovered in Leiden almost a century ago. For the past 15 years, attention has focused on copper oxide materials (cuprates), but recent discoveries that MgB_2 and doped C_{60} are superconducting at unexpectedly high temperatures have moved the main group elements back into the limelight that they occupied in the early days of superconductivity. On page 272 of this issue, Eremets *et al.* (*1*) show that under high pressure, boron becomes superconducting. The result fills an important gap.

In the decades after World War II, main group and transition metals were found to behave very differently with respect to their superconducting properties. It turned out that the periodic table affords a natural basis for comparing superconductors and searching for new ones. It is not obvious that this should be so: The periodic table was developed from chemical behavior, where the energy scales are two or more orders of magnitude larger than superconducting energy scales. Nevertheless, clear patterns emerge (see the figure).

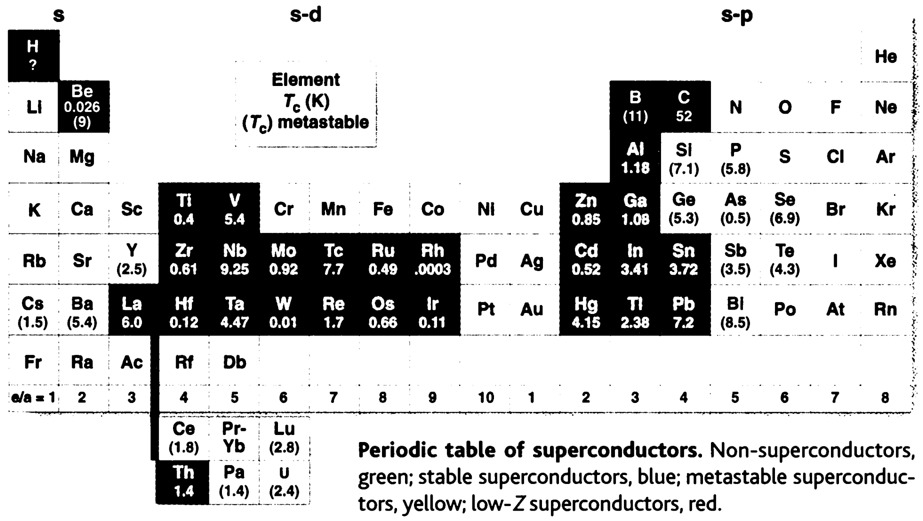
The value of the periodic table was recognized particularly by B. T. Matthias and co-workers. By noting the empirical trends, many new superconductors were discovered in the three decades after World War II. Far from being rare, superconductivity was found to be a commonly occurring ground state of nonmagnetic metals. During the same period, Bardeen, Cooper, and Schrieffer (BCS) discovered the microscopic pairing theory of superconductivity. BCS theory, although not successful in predicting new superconductors, was very successful in understanding and predicting the properties of known classes of superconductors (*2*).

A fruitful interaction between theory and experiment led a majority of scientists to believe that all superconductivity was due to a phonon-mediated electron pairing interaction. According to the simple BCS approximation, the transition temperature (T_c) is given by

$$T_c = 1.14\theta_d \exp - (1/NV) \qquad (1)$$

where θ_d is a representative average of the phonon energies involved in the coupling, N is the electron density of states at the Fermi level, and V is the electron-phonon scattering matrix. This equation is valid when the dimensionless electron-phonon coupling, NV, is small with respect to unity. It can be readily seen that for $NV < 0.3$, as is the case for light elements, one should not expect T_c's above 10 to 15 K, as is observed (see the figure). When the coupling becomes stronger, the BCS solutions involve more parameters as discussed by Eremets *et al.* (*1*). For the present purposes, however, the simple BCS approximation will suffice.

Eq. 1 captures the essence of why superconductors can be grouped according to their position in the periodic table. The light main group elements, from Be to S, become superconducting below ~10 K (with the exception of carbon, see below) if they are metallic or can be collapsed into a metallic phase by pressure or by quenching from the vapor. This can be understood in terms of their broad, featureless sp conduction bands and the weak



Periodic table of superconductors. Non-superconductors, green; stable superconductors, blue; metastable superconductors, yellow; low-*Z* superconductors, red.

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